THE ERS-1 SYNTHETIC APERTURE RADAR AND SCATTEROMETER

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ESA's first remote-sensing satellite ERS-1 is designed to fulfil oceanographic mission requirements. The instrument payload includes an altimeter, an along-track scanning radiometer, and the active microwave instrument (AMI). The AMI incorporates a synthetic aperture radar and a scatterometer, both systems working at C-band. This paper describes the instrument, some of the design rules, and the hardware implementation. The AMI is being designed and developed by Marconi Space Systems.

1. INTRODUCTION

In 1984 the European Space Agency (ESA) initiated the development phase of the first European remote sensing satellite, ERS-1(1). This satellite, which is to be launched in 1989, has been designed to carry a payload of sensing instruments for Earth observation. The ERS-1 satellite will form a major part of continuing satellite remote sensing programmes, established notably by the NASA LANDSAT series of satellites.

ERS-1, illustrated in fig. 1, is conceived primarily as fulfilling an oceanographic series of objectives. In so doing it relates closely to the SEASAT satellite launched by NASA in 1978. Both satellites were designed around a package of microwave instruments. Both satellites include a synthetic aperture radar (SAR), but whereas the SEASAT SAR(2) operated at L-band, the ERS-1 SAR will function at C-band. The SEASAT mission, although curtailed by equipment malfunction, contributed significantly to knowledge of the ocean structure and dynamics, through aspects of glaciology, geodesy, and climatology(3).

An example of an image generated by the SEASAT SAR, demonstrating the potential of such systems, is shown in fig. 2. The image records the radar reflectivity of an area of the English Channel measuring about 40 km × 55 km. The spatial resolution is around 25 m. A portion of the English coast is visible in the right hand top corner of the image, while large scale current patterns dominate the sea return. Well developed wave trains can be seen intermittently across the image, while ships and their associated wakes can be detected. The SEASAT radar was in low earth orbit at a height of approximately 800 km. Typical image products obtained from a satellite SAR will be found in references [4–6].

The ERS-1 sensor package comprises an altimeter, an along-track scanning radiometer (ATSR) and microwave sounder, and an active microwave instrument (AMI). The altimeter, operating at Ku-band, is designed to measure satellite height to high relative accuracy (±10 cm), enabling geoidal variations over the ocean surface to be determined. The altimeter will also provide information on significant ocean wave height over the subsatellite region sensed by the instrument. The ATSR is a three channel infrared radiometer, designed to measure sea surface temperature to an accuracy of ±0.5°K over a 500 km swath. The microwave sounder, with which the ATSR is combined, will sense atmospheric water vapour content, and both the ATSR and microwave sounder can be used over land and ice to record their associated radiances and emissivities.

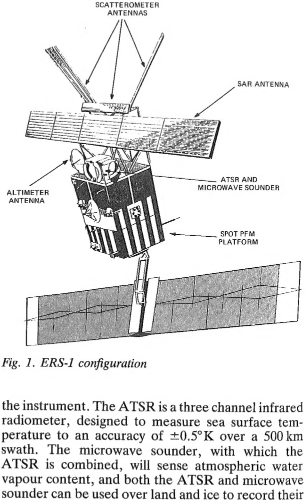

Fig. 1. ERS-1 configuration

The active microwave instrument (AMI) will operate in two modes, with each mode utilising a separate antenna system. As a synthetic aperture radar, the AMI will be able to image the Earth's surface to a spatial resolution of 30 m over an 80 km swath. Over the ocean, the AMI will have the capability to determine ocean wavelength and direction. In the second mode, the AMI functions as a C-band scatterometer, where multiple radar returns from a measurement cell on the sea surface are used to estimate surface wind speed and direction. The variation of the radar backscatter with wind direction exhibits (unequal)

Fig. 2. SEASAT SAR image of English Channel

peaks when the radar look is upwind or downwind, while increasing wind speed is related to increasing backscatter. The instrument utilises three measurements at a single frequency and polarization, but diverse in angle, to provide the necessary multiple measurements to resolve the directional ambiguities in the wind vector.

The purpose of this paper is to describe some of the engineering details of the ERS-1 AMI, illustrating how image quality and geophysical requirements have been translated into a radar design. In the following section the modes of the AMI are further described, followed by a discussion of the instrument requirements and the hardware implementation.

The AMI is currently being developed as an end-to-end radar system by Marconi Space Systems Limited for the ERS-1 prime contractor Dornier System GmbH (Germany). GEC Research Limited, under subcontract to Marconi Space Systems, is providing support in system design activities.

2. AMI INSTRUMENT MODES

SAR Image Mode

The radar geometry of the SAR is shown in fig. 3. An orbit with nominal spacecraft altitude of 785 km has been chosen, being consistent with satellite lifetime considerations, instrument coverage, and radar constraints, such as available transmitter power.

The rectangular antenna is aligned along the satellite's line of flight to direct a narrow azimuth beam sideways and downwards onto the Earth's surface. The elevation beam illuminates a strip on this surface, and as the satellite orbits, the antenna footprint sweeps a continuous swath. The elevation beamwidth of 5.4° is sufficient to maintain an image requirement, or image quality, over the 80 km swath when errors such as antenna mis-pointing are taken into account. The swath position is fixed by an angle of incidence at the centre of the swath of 23°, when the centre is at a stand-off range of 292 km from the sub-satellite track.

Antenna stowage and deployment contraints limit the size of the antenna, particularly the length of the antenna in the along-track direction. ERS-1 will use an antenna length of 10 m. At the frequency of 5.3 GHz, the width of the radar footprint on the ground is about 4.5 km and this dimension can be equated with the spatial resolution in azimuth of a real aperture radar imaging system. However, significant improvements may be achieved by the aperture synthesis technique(7). This technique allows an aperture to be synthesized from coherent radar returns, using the scanning motion of the radar platform.

Aperture synthesis utilises the real antenna as one element of a longer array to be constructed. Each pulsed radar return is sampled and recorded, and is identified with the position of the real antenna phase centre at the transmission/reception instant. As the platform translates, a sequence of these pulse returns are digitized and stored over a distance cor-

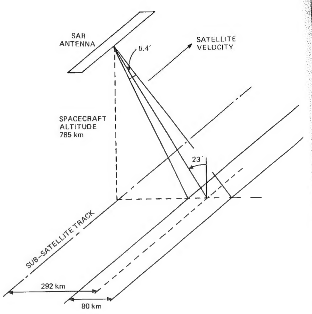

Fig. 3. SAR geometry

responding to the length of the synthetic aperture. These pulses contain the varying phase histories of the radar reflectors on the surface within the antenna footprint. In a subsequent processing operation, the stored radar returns are summed with phase shifts appropriate to an array which provides the desired resolution. The processing is continuous in that "new" pulses are accumulated, while "old" pulses are discarded. (Equivalently, this process may be regarded as a matched filtering operation on the Doppler-shifted radar return).

The standard result of aperture synthesis(7) demonstrates that in the limit, when the synthetic aperture is of length equal to the width of the radar footprint, then a spatial resolution of one half the real antenna aperture can be achieved. For ERS-1, this implies a resolution in azimuth of 5 m.

In the range direction, high resolution is achieved by transmitting radar pulses of short duration, or by pulse compression techniques as in the case of ERS-1. The compression of the pulse gives rise to a second matched filtering process in an orthogonal direction to the azimuthal aperture synthesis. The two-dimensional filtering operation provides an image output for all resolution elements within the image. For ERS-1, the spatial resolution is 30 m by 30 m.

Certain radar system parameters, in particular the pulse repetition frequency (prf) can be selected without specific reference to image quality. In choosing the pulse repetition frequency, three criteria(7) have to be considered:

(i) the prf must be low enough to permit the radar return from the desired swath to be received between two pulse transmissions.
(ii) the radar return from the swath should not be ambiguous with the sub-satellite return, and
(iii) the prf should be high enough to sample the

Doppler bandwidth of the radar return adequately.

With the geometry as defined, these three criteria can be satisfied, with the resulting pulse repetition frequency in the region of 1700 Hz.

The image formation from the raw radar data, the aperture synthesis, is referred to later in this section.

SAR Wave Mode

The radar geometry for SAR wave mode is identical to that of the SAR image mode (fig. 3). The SAR wave mode is intended to operate over the ocean surface providing a 5 km × 5 km image patch of the ocean every 200 km or 300 km, selectable along the ground track. The resulting data is processed as in the image mode to provide high resolution images of the ocean surface. Post-processing by a two-dimensional Fourier transform produces a two-dimensional spectrum of the ocean wave images[5,6].

Wind Scatterometer Mode

The geometry of the wind scatterometer mode is shown in fig. 4. Three sideways-looking antennas direct fore, mid, and aft beams at a swath of width 500 km on the Earth's surface. As in the SAR, the scatterometer antenna beams successively sweep a continuous swath as the platform translates.

The near edge of the swath is at a stand-off of 225 km from the sub-satellite track. Thus the SAR swath will lie within that of the wind scatterometer.

The beams are inclined so that the footprints of the fore and aft beams are at an angle of ±45° to the mid-beam footprint, as shown in fig. 4. The swath can be envisaged as comprising cells of dimension 50 km × 50 km, with ten cells spanning the swath. Energy returned from each cell in each beam is integrated and used to provide a measure of the radar reflectivity of the ocean surface, this reflectivity being expressed in terms of the normalised radar scattering cross-section, σ_0.

Fig. 5 illustrates the variation of σ_0 with varying wind direction. Since the mechanism generating the radar backscatter is Bragg scattering from wind-driven waves on the ocean surface, and since the energy in these waves increases with wind velocity, it may be anticipated that the backscatter increases with wind velocity. The typical curve shown in fig. 5 will be shifted upwards with increasing wind speed.

As the satellite translates, each beam provides one measurement of the radar reflectivity from each cell. Three measurements, separated by a short time delay, can be extracted from each cell. The best fit of these measurements to the family of curves for all wind speed serves to determine wind speed and direction.

The wind scatterometer is designed to operate over a range of wind speeds from $4\,\mathrm{m\,s^{-1}}$ to $24\,\mathrm{m\,s^{-1}}$ providing accuracy of $2\,\mathrm{m\,s^{-1}}$ (or 10%, whichever is greater) with a directional accuracy of ±20°. The wide-swath enables a wind field to be developed from the individual cell estimates.

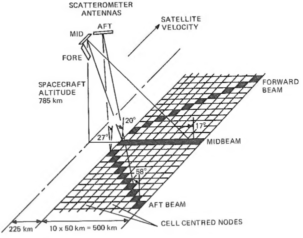

Fig. 4. Scatterometer geometry

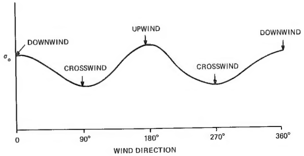

Fig. 5. Variation of σ_o with wind direction

Processing for the Different Modes

The SAR image is formed by passing the digitised radar echo through a so-called 'matched filter' in both the range and azimuth directions[8].

The range filtering is performed first. It consists of a convolution of the radar return with a reference function which is the impulse response of the radar. This reference function is generated from the replica of the transmitted waveform previously described.

Because of the motion of the satellite, a particular target is located at a different range in successive radar returns. This so-called 'range-walk', or 'range migration', must be corrected prior to azimuth processing.

Also, because of the motion of the satellite, each target exhibits a unique Doppler history while it is within the radar beam. It is this Doppler shift that provides the opportunity for azimuth compression. The azimuth data are divided into a number of sub-apertures by dividing the Doppler space into six equal intervals (hence a 'six-look' radar). This is achieved by Doppler tracking of the return echo. Each look is then processed by a convolution with a reference function. This reference function is dependent on the radar illumination pattern and satellite pointing.

Non-coherent averaging of the looks sacrifices spatial resolution for radiometric resolution. The same radar data, which could provide a potential resolution

of 5 m, is used to give a 30 m resolution at improved radiometric resolution. Further look-integration provides 100 m spatial resolution with corresponding radiometric improvement. Misregistration of the looks can produce a defocussing of the image and this is controlled within the processor by autofocus algorithms.

Several post-processing operations are required to ensure that the final product meets the required image quality including corrections for ratiometric errors (calibration) as well as geometric distortions.

The data is presented to the wind processor in three sets, each set corresponding to the data collected from a single antenna. The first stage of the processing is to put these three sets of data onto a common grid to correct for geometric distortions. At this stage radiometric corrections may also be made by using calibration data. This process is called 'σ_0 extraction'.

Following σ_0 extraction the wind speed and direction can be derived by using the independent values of σ_0 with a derived experimental relationship. This produces a best fit to the actual wind speed and direction within certain confidence levels. These confidence levels form part of the specification of the scatterometer.

3. INSTRUMENT REQUIREMENTS

The instrument requirements for certain accuracies in the measurements of geophysical parameters do not simply translate into performance requirements of the AMI itself; for example, the accuracy of the wind vector estimates is strongly linked to the model of the interaction between the radar and the sea surface. Hence, an end-to-end performance specification for the individual instruments is difficult both to specify and to verify. The performance specification for the AMI is therefore given in terms of the basic output from each of the individual instruments.

For the SAR, this performance covers the overall system including the processor used to convert the raw signal into a final image, and is mainly concerned with the two-dimensional response of this system to an isolated point target. In the case of the scatterometer, the instrument output consists of three independent measurements of the radar cross-section of the sea at each point on a regular grid with spacing 25 km. Performance specifications are placed upon each of the individual scatterometer beams used to derive these measurements. The scatterometer system performance includes the radar/sea interaction model and the preliminary scatterometer processor, but stops short of the conversion of the backscatter values into wind vector estimates.

Given these requirements on the AMI performance, it is the task of the radar designer to translate the performance figures into engineering terms, thereby placing a specification on the instrument subsystems and on the combined error contribution. The selection of a particular value for one of the system parameters can influence a number of the measured performance figures. In the case of the SAR, for example, choice of a value for the pulse repetition frequency affects both the coverage and ambiguity performance.

In this section, the description of the performance specification in terms of system values such as bandwidths and signal-to-noise ratio is briefly outlined. Attention is focussed on some particularly interesting aspects relating to the SAR in order to give an indication of the types of trade-off which must be conducted.

Reference Geometry

Before placing detailed performance requirements upon any system, it is clear that a reference position or set of positions must be specified since many of the performance parameters are functions of geometrical variables such as earth incidence angle and target to satellite slant range. For the AMI, a reference orbit has been selected and the performance values are given at a particular position within that orbit. Specifically, the spacecraft altitude is given as 785 km above a locally spherical earth of radius 6366 km. With this geometry as baseline, a point on the earth can be fixed by its local angle of incidence (or equivalently by the angle subtended at the satellite).

The performance requirements in each of the AMI modes will now be addressed.

SAR Image Mode

As stated above, the SAR specification includes the image processor and so is chiefly concerned with parameters which can be measured from the final image. The specification includes fundamental parameters such as the radar frequency and polarisation. The performance requirements are given in table 1 and some of the more important parameters are briefly discussed below.

a) Impulse Response Function Measures

SAR uses coherent processing techniques in two orthogonal dimensions to produce high resolution radar images. In both the range dimension (where the pulse is "chirped") and the azimuth dimension, the raw signal has a linear frequency-modulated structure and the processing is realised by cross-correlation with replica functions whose phase variations match those of the signal. If no weighting is applied during the correlations, the response to an isolated point target has a $\sin^2 x/x^2$ envelope in each dimension (after square-law detection). If the correlation covers a frequency range of B Hz, the time resolution of the impulse response function as measured at its -3dB points is given by $0.886/B$ seconds. For the spatial resolution requirements of table 1, the respective bandwidths are 12 MHz in range and 196 Hz in azimuth. However, the peak sidelobe of a $\sin^2 x/x^2$ function is too high (around 13 dB) to meet the specification and it is necessary to introduce weighting into the correlations to push energy from the sidelobes into the mainlobe. This necessitates an increase in the processing bandwidths to maintain

TABLE 1

SAR Image Mode Performance Requirements

Performance Parameter	Requirement
Radar Frequency	5.3 GHz ± 750 kHz
Polarization	Vertical 30 dB cross suppression
Coverage – Swath Length	10 minute capability
– Swath Width	Minimum of 80.4 km
(Reduced Quality)	Minimum of 99 km
Impulse Response Function	
– Spatial Resolution (Range (x))	$\leqslant 26.3$ m
– Spatial Resolution (Azimuth (y))	$\leqslant 30.0$ m
– Peak Sidelobe Ratio	$\leqslant -20$ dB in 10 x by 10 y region $\leqslant -25$ dB outside 10 x by 10 y region
– Integrated Sidelobe Ratio	$\leqslant -8$ dB
– Ambiguity Ratio (Range)	$\leqslant -31$ dB
– Ambiguity Ratio (Azimuth)	$\leqslant -22$ dB
Pixel localisation	
– Range	± 0.9 km
– Azimuth	± 1.0 km
Incidence Angle at Mid-Swath Position	23°
Radiometric Resolution	$\leqslant 2.5$ dB for 10.7 dBm^2 target
Dynamic Range	Signal power range equivalent to $-18\text{ dB} \leqslant \sigma_0 \leqslant 3$ dB with additional 12 dB headroom
Radiometric Measurement Accuracy	Better than 1 dB
Radiometric Stability	Better than 0.95 dB

the spatial resolution performance. In addition, there will be phase and amplitude mismatches from error sources between the signal and the correlation replica which will cause broadening of the mainlobe of the response (and therefore resolution degradation) and the appearance of spurious peaks of energy in the sidelobes. In fact, since each mismatch error contains linear, quadratic, cyclic and random variations, it is necessary to perform simulations in order to derive the bandwidths, processing weighting and permissible mismatch errors. The error budgets can then be assigned to the various subsystem components. Current ERS-1 performance is achieved using respective range and azimuth bandwidths of 15.5 MHz and 222 Hz and respective (Hamming) weightings of 0.75 and 0.84.

Another important aspect concerns ambiguity ratios. Because the SAR receives echoes in discrete time windows between pulses transmitted at a fixed rate determined by the prf, it cannot distinguish between the range returns which come from beyond the far edge of the swath but which occur during a later reception period, nor can the SAR separate those points in the azimuth dimension whose Doppler frequencies differ from that of the target by an integer multiple of the prf. Processing produces a response function for the ambiguities as well as the target and hence, if the target is of low reflectivity the ambiguities may predominate, giving false reflectivities for the imaged scene. Although there is some mismatching of these ambiguities in the processing which aids suppression, the essential contributors are the prf, which determines the location of the ambiguities, and the range and azimuth antenna patterns. Selection of the prf is further complicated by the need to achieve the coverage round the orbit in a varying geometry, (which means a shift in the echo window must be accommodated). Trade-offs are again necessary.

b) Radiometric Resolution

The coherent processing introduces a signal-dependent noise term which is caused by constructive and destructive interference between many small scatterers within each resolution cell. This noise (coherent "speckle") makes the image from a uniform scene appear grainy, but the effect can be reduced by some form of non-coherent averaging. When a number, L, of independent looks of the same mean signal-to-noise ratio (SNR) are combined, the standard deviation in the measurement reduces as $1/\sqrt{L}$. The radar is required to measure reflectivities accurately, and the specification on radiometric reso-

lution provides a limit on this target scene variation. The specification requires the system to achieve a certain number of looks, effectively independent images, at a minimum mean SNR.

The required azimuth bandwidth for the spatial resolution requirement is approximately 220 Hz, and 1320 Hz are available, hence 6 independent looks can be achieved in azimuth. The mean SNR calculation is complicated by the effect of the azimuth beam pattern, causing SNR to vary between looks. The achievable mean SNR is dictated by the radar equation (adapted for the synthetic aperture radar case). Again trade-offs in a large number of systems parameters can be performed. However, once the contributions from the systems components are known, the only variable in the radar equation is the target cross-section σ.

Hence the performance is given in terms of the value of σ which, for the given number of looks, produces the mean SNR value required to achieve the radiometric resolution specification of $\gamma = 2.5$ dB, where γ is defined as

$$\gamma = 10 \log_{10} \left(1 + \frac{1 + \sigma_N/\sigma}{\sqrt{L}}\right)$$

for L independent looks, with σ being the target cross-section and σ_N the equivalent cross-section of the noise. If the mean SNR requirement cannot be achieved for the required value of σ, the number of looks can be slightly increased by overlapping the frequency bands thereby reducing the SNR required, although there is a limit to the increase which can be realized. Analysis into overlapped looks and increasing the bandwidth in azimuth is being performed.

These two examples illustrate the complexity of the performance requirements for a SAR and indicate how involved the verification processes can be.

SAR Wave Mode

In wave mode, the SAR images 5 km square patches of sea which are transformed to the frequency domain for subsequent processing and interpretation, but the performance requirements are still placed on the intermediate image product and are essentially identical to those for the image mode (with the notable exception of a reduced localisation accuracy).

Scatterometer Wind Mode

The wind mode performance requirements are given in table 2. They show much in common with the SAR mode in terms of the types of measurement used to characterise the performance, although the parameters themselves arise through entirely different circumstances. The scatterometer is a non-

TABLE 2

Wind Scatterometer Mode Performance Requirements

Performance Parameter	Requirement
Radar Frequency	5.3 GHz ± 750 kHz
Polarization	Vertical 30 dB cross suppression
Coverage – Swath length – Swath width – (Full Performance)	Continous Capability At least 500 km 400 km
Impulse Response Function	
– Spatial Resolution (Range (x))	⩾ 50 km
– Spatial Resolution (Azimuth (y))	⩾ 50 km
– Ambiguity Ratio/Peak Sidelobe ratio	⩾ 60 dB more than one cell distant
– Spectral Resolution (Range (x_s))	⩾ 0.02 km^{-1}
– Spectral Resolution (Azimuth (y_s))	⩾ 0.02 km^{-1}
– Integrated Ambiguity Ratio	Accounted for in K_p budget – assessed against target scenes
Measurement Cell Localisation	To within 5 km
Aspect Angles	± 45° ± 1°, 90° ± 1°
Inclination Angle of Mid-Swath from Nadir	29.3°
Radiometric Resolution	Specification related to σ_0 tables
Dynamic range	Related to minimum and maximum σ_0 tables
Radiometric Measurement Accuracy	Better than 1 dB
Radiometric Stability	
– Interbeam	Better than 0.46 dB
– Common Mode	Better than 0.57 dB

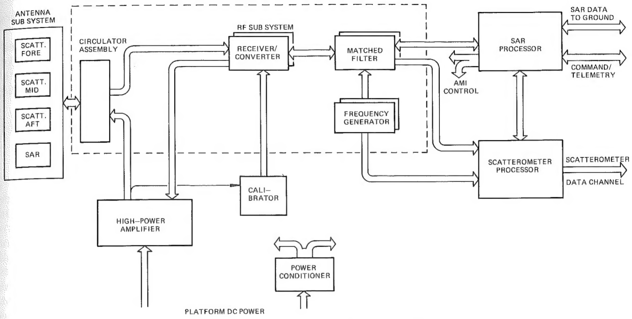

Fig. 6. The active microwave instrument (AMI)

coherent device and uses a weighted average of a number of returns taken over a particular area to reduce the standard deviation in the estimate of the mean radar backscattering coefficient. Hence the impulse response is derived in a complicated manner involving, for example, the azimuth gain pattern, the number of combined returns, the frequency filter characteristics and any weighting applied in the summation. It is therefore necessary to assess each contributory component and then conduct simulations to gauge performance, with shortfalls necessarily feeding back into the individual requirement specifications on these components. Similarly the radiometric resolution calculations are somewhat more complex than for the SAR, being expressed in terms of a K_p factor defined similarly to γ but including other contributing factors due to ambiguities, frequency aliasing and system non-linearities. Since the system must detect a variety of wind speeds and directions, it is also necessary to include maximum and minimum backscattering values at each incidence angle in the swath. The scatterometer performance must generally be verified across the whole swath and throughout the orbit (rather than for the SAR where simple scaling is often adequate).

4. THE AMI INSTRUMENT

A block diagram of the on-board AMI instrument is shown in fig. 6. The blocks shown represent discrete equipment items mounted within the satellite's Payload Electronics Module (PEM). The antennas and their associated r.f. switches (circulator assembly) are external to the PEM.

During image-mode operation, the command to generate a radar pulse is initiated by the SAR processor. The matched filter equipment takes this signal, together with the intermediate frequency signal from the frequency generator, to produce a so-called 'short pulse' at a pre-determined phase of the i.f. signal. This short pulse is used as the input to a dispersive delay line (Surface Acoustic Wave (SAW) device), which produces the linear FM, or 'chirped', pulse centred at the intermediate frequency. The length of the expanded, 'long', pulse (37.1 μs) is defined by the dispersive line to be consistent with the requirements of the radiometric resolution, while the FM deviation is defined by the requisite spatial resolution of the radar. The time-bandwidth product of this pulse is close to 600.

The expanded pulse output from the matched filter is passed to the receiver and upconverter where it is mixed with the local oscillator signal produced within the frequency generator. The level of the RF output pulse is controlled by an AGC loop. This output must then be amplified by approximately 45 dB at the high-power amplifier.

The output of the high-power amplifier subsystem is routed via waveguide through the circulator assembly to the SAR antenna. It is not necessary for any circulator to switch between transmit and receive whilst the AMI stays in a particular operating mode.

Similarly the echo signal received by the SAR antenna is routed via waveguide through the circulator assembly to the input of the receiver. Due to the high power reflected back from the antenna during transmission, the receiver must be provided with an input limiter. The receiver radar echo is then amplified in a low-noise amplifier and mixed with the local oscillator signal to provide a signal at the intermediate frequency at the input to the matched filter.

The matched filter unit can be used either to route the echo signal directly to the SAR processor or to perform range compression. In the former case, the unit merely serves to amplify the received signal to

the desired level. In this mode – the on-ground range compression mode – a replica of the transmitted signal is derived via the calibration sub-system which then serves as the reference during ground processing range compression. In the latter mode – the on-board range compression mode – range compression is performed by a SAW compressor within the matched filter.

The matched filter processes the echo signal and routes it to the SAR processor, where it is resolved into in-phase and quadrature components. These component signals are digitised by analogue-to digital converters and input to a dedicated memory. The latter provides a buffer so that the output data form a continuous bit stream at a lower rate. The ground processing requires data in addition to the radar echo in order to produce the necessary image. This 'auxiliary data' is inserted into the range memory by the instrument control unit to become part of the data stream[9].

The basic operational parameters of the AMI in SAR image, SAR wave and Scatterometer wind modes are given in table 3.

During wind scatterometer mode, a transmit pulse is produced at the intermediate frequency by the scatterometer processor. The IF pulse is amplified by the matched filter unit, converted to an RF signal in the receiver/converter unit and amplified by the high-power amplifier. The transmit signal is routed to the correct antenna by the circulator assembly, which in this mode is under the control of the scatterometer processor.

The received signal is downconverted, amplified by the matched filter unit and routed to the scatterometer processor.

The return signal has a significant Doppler component of about 100 kHz in fore and aft beams caused by the relative velocity of the satellite with respect to the target. This Doppler component must be removed, and compensation is performed on the echo signal using satellite altitude data supplied from the ground via the instrument control unit.

The echo signal is digitised and input into a dedicated wind memory. System noise samples are taken at convenient intervals and are also input into this memory. The noise samples are used for calibration of the signal return from the ocean surface.

5. ON BOARD HARDWARE IMPLEMENTATION

SAR Processing Sub-system

The SAR processor shown in fig. 7 acts as the interface between the AMI and the platform On-Board Data Handling (OBDH) system for receipt of commands from and telemetry of instrument status data to the ground station. It initiates SAR transmit signals, performs coherent detection and quantisation of SAR echoes, provides buffering for SAR data and makes it available to the Instrument Data Handling and Telemetry (IDHT) system for transmission to the ground.

The SAR processor also provides internal control of the AMI using the integral microprocessor-based Instrument Control Unit (ICU). The ICU's functions include configuration of the instrument for the required operational mode, monitoring of AMI functions, and fault detection. The ICU must be able to control all AMI functions whilst the satellite is out of contact with the ground station.

The following principal AMI operational modes are defined:

- Image mode
- Wave mode
- Wind scatterometer mode
- Interleaved wind/wave mode
- Calibration modes, in which calibration of one or more of the instrument's operational functions (image, wave or wind) takes place

TABLE 3

Basic Parameters for AMI operational modes

Parameter	SAR image mode	SAR Wave mode	Scatterometer wind mode
Radar centre frequency	5.3 GHz	5.3 GHz	5.3 GHz
FM chirp bandwidth	15.5 MHz	15.5 MHz	–
Pulse repetition frequency	1700 Hz nom.	1700 Hz nom.	98 Hz (fore, aft). 115 Hz (mid)
Transmitted pulse length	37.1 μs	37.1 μs	130 μs (fore, aft). 70 μs (mid)
Peak RF power (at tube output)	4.8 kW	4.8 kW	4.8 kW
Mean DC power required	1267 W	318 W (max)	448 W
Swath width	80 km	5 km	500 km
Spatial resolution	30 m × 30 m	30 m × 30 m	–
Radiometric resolution	2.5 dB	2.5 dB	–
Measured wind speed range	–	–	4 m/s to 24 m/s

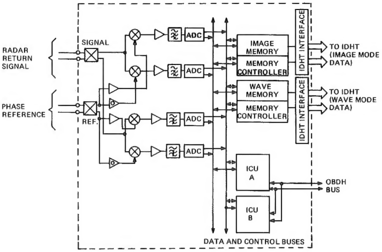

Fig. 7. The SAR processing sub-system, showing redundancy

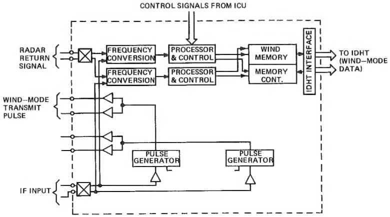

Fig. 8. The scatterometer processor

- Pause mode: all AMI equipment is powered and thermally stable
- Heater mode: an energy-conserving state, in which only equipment items having long thermal time constants will be powered.
- Standby mode: only the instrument-control is powered
- Off mode: All AMI equipment is off. External heating is provided by the platform

The SAR processor also provides basic timing and control signals for the scatterometer processor for wind-mode control.

Radar-pulse timing signals for SAR modes are generated by the SAR Processing sub-system and passed to the RF subsystem. The radar return signal is detected within the SAR processor and quantised by one of two redundant SAR detectors at a sampling rate of 19 MHz, to produce 5616 complex samples per image mode return. Data is transferred from the detectors at a rate of 228 Mbit/s and the quantised data from a complex radar return are stored in the image or wave memory.

To ensure loss-free transmission of data to the IDHT in image mode, it is necessary to provide three image memories. In addition to the image data, auxiliary data are required to be transmitted to the ground processing facility for the correct interpretation of the data gathered. Data is output from the image memory on demand from the IDHT, in eight-bit word format, at a rate of approximately 105 Mbit/s.

Scatterometer Electronics Subsystem

The heart of the Scatterometer electronics, shown in fig. 8, is its microprocessor-based processor and controller, which coordinates all wind-mode activities. The Scatterometer electronics initiates transmit signals, detects and digitises the radar echoes and noise samples, and performs preliminary data processing to compensate for system noise and incurred Doppler shifts, prior to transmission to ground.

The Scatterometer electronics receive wind mode initiation signals and parameter values from the SAR

processing subsystem and pass output data to the IDHT.

Control signals for the switch matrix assembly, to route transmit energy to the appropriate antennas in wind mode, are delivered to the switch matrix controller from the Scatterometer electronics' internal signal generator.

RF subsystem

The RF subsystem is required to generate, switch, and receive the signals necessary for the operation of both the SAR and Scatterometer. It contains the transmit and receive parts in addition to providing the master oscillator for all instrument frequencies and switch function antenna selection. The RF subsystem is shown as a block diagram in fig. 9.

The matched filter performs pulse expansion and frequency modulation (chirping) on SAR transmit pulses and pulse processing on SAR receive echoes.

In image and wave modes, the SAR processor provides a signal at the radar pulse repetition frequency which is gated by a narrow pulse signal to form an impulse. These impulses are applied to a SAW dispersive delay line to provide the linear FM signal. The chirp signal is then amplitude-limited to remove all the amplitude ripples (resulting largely from triple-transit effects) and then time-gated to remove edge distortions and other consequences of triple-transit effects.

In wind mode, the transmit section provides a bypass path for the Scatterometer signals at 98 or 115 Hz pulses.

In the receive section, a bypass path is provided for the SAR image and wave signals for an on-ground compression operation and for the Scatterometer wind mode. This bypass path has an amplifier to provide the appropriate receiver gain for the particular mode of operation.

For the on-board compression mode of operation for the SAR image and SAR wave signals, the receive section provides SAW dispersive delay lines with characteristics that are the conjugates of the chirp generators in the transmit section. Weighting networks are inserted ahead of the SAW dispersive delay lines to reduce the peak side-lobes and the integrated side-lobe ratio of the compressed signals. To ensure correct tracking of the transmit and receive SAW dispersive delay lines over the operating temperature, the SAW elements use the same acoustic substrate and are temperature stabilised.

An amplifier with a programmable 30 dB gain range is inserted into the signal path to compensate for gain changes in the receiver over the operating life of the AMI. This gain is variable in 0.5 dB steps over the 30 dB gain range.

All gating signals required for the RF subsystem are derived within the matched filter from the original radar pulse signals provided by the SAR processor and Scatterometer processor.

The switch matrix assembly provides high-power RF connections between the HPA, and the receiver, and any one of the four antennas. It consists of the switch matrix, comprising six switchable ferrite circulators, and the switch matrix controller. The switch matrix is nonredundant.

High-power amplifier

The high-power amplifier (HPA) amplifies the low-power output from the RF subsystem to the level required for radiation at the antennas. A block diagram of the HPA is shown in fig. 10. The tube assembly performs RF amplification using a high-power travelling wave tube amplifier system.

Calibration Subsystem

The calibration subsystem is shown in fig. 11. This subsystem forms a vital part of the AMI internal calibration.

A sample of the transmitted pulse is taken, delayed and fed into the receiver to monitor and calibrate out drifts in receiver gain. The calibration pulse is delayed by 45 μs for the SAR, and 135 μs for the scatterometer, to synchronize with signal sampling timing requirements. These delays are introduced using SAW delay lines.

There is also a requirement for the calibration subsystem to inject random noise signals, at a range of attenuations, into the input of the AMI receiver. These variable noise signals are used for regular characterisation of the AMI receive path gain.

In addition to the AMI internal calibration requirements outlined above, the calibration subsystem is required to provide a 'replica' of the transmitted pulse for on-ground range compression. This replica is identical to the calibration pulse, but is injected into the receiver at an IF injection point.

Antenna subsystem

The antenna subsystem consists of one SAR and three wind-scatterometer antennas. All are used for both transmit and receive functions in their respective modes.

The proposed SAR antenna, fig. 1, consists of 10 electrical panels, each with 24 horizontal radiating waveguides with 24 slots each. Two electrical panels make up one mechanical panel. The radiating waveguides are fed via rotated coupling slots from a feed waveguide across each electrical panel. The five mechanical panels are folded during launch and deployed when the satellite is in orbit.

The wind scatterometer is composed of three antennas, as shown in fig. 1. The central one, sited on top of the SAR antenna, is the mid beam antenna and the other two, stowed during launch on both sides of the antenna support structure, are the side beam antennas (fore and aft).

The side beam antennas are both 3.6 m long and 0.46 m wide and have two sub-panels 1.8 m long. The radiating side of the antenna is a set of six slotted waveguides. As it is not deployable, the mid beam antenna has no mechanism, though rigid element fixing during launch and 'fixed-free' attachment in orbit is foreseen to avoid thermally-induced stresses

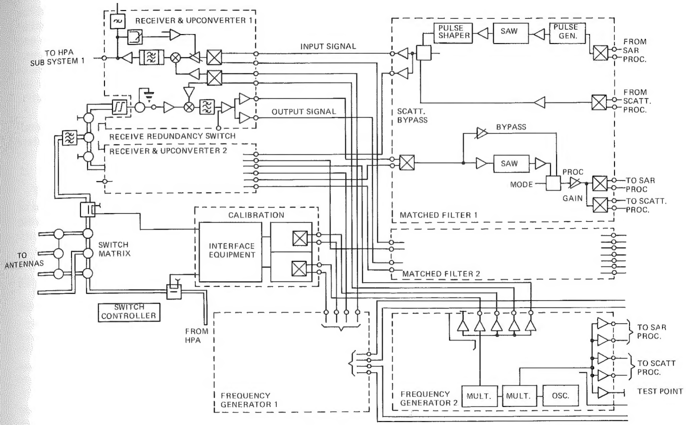

Fig. 9. The RF sub-system

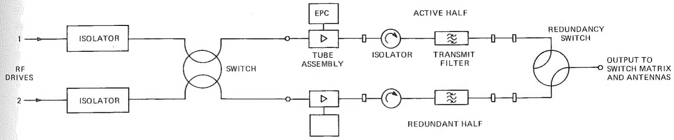

Fig. 10. The high power amplifier (HPA)

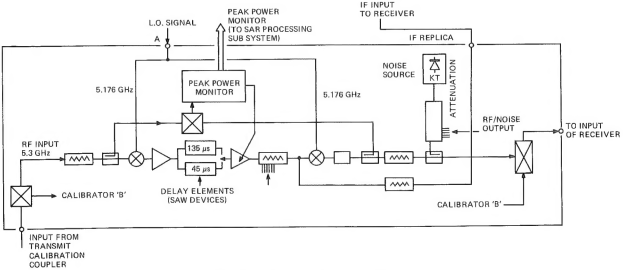

Fig. 11. The calibrator sub-system

due to the difference in materials of the antenna and its support structure.

AMI redundancy concept

In general, cold redundancy is employed within the AMI. Each equipment item is provided with a standby unit which is unpowered and inoperative until required. Active and redundant units are cross-strapped and the redundancy configuration is selected by the ICU, after consultation with the ground, which then enables power only to required units.

The HPA is internally redundant and employs a coax switch on its input to allow either amplifier tube assembly to be connected to the RF input signal. The tube is selectable by either a latching waveguide switch or circulator (a design choice).

In certain cases it is neither necessary nor desirable to provide fully cross-strapped cold redundancy. This applies particularly to some large modularized memory stores within the SAR processor. Here partial redundancy is employed so that additional memory modules are provided to replace any that may fail. It is, of course, important to design each module in such a way so that a failure of any module does not prejudice the operation of other similar modules.

6. CONCLUSIONS

An outline of the ERS-1 radar package has been presented. The ERS-1 satellite will provide operational and pre-operational oceanographic data during the early 1990's. The design and implementation in hardware is part of a programme for a satellite development which closely involves space engineers, scientists, and data users.

The design of the active microwave instrument has presented a series of varied theoretical and technical challenges. The AMI is an advanced end-to-end radar package which has been designed around tightly specified requirements. The satisfaction of these requirements involves detailed aspects of the radar system, satellite orbit, and attitude, geometry, and operational considerations.

The engineering challenge is particularly demanding and the hardware implementation employs state of the art space technology in many areas.

7. ACKNOWLEDGEMENTS

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